

CCSDS RECOMMENDATIONS FOR RADIO FREQUENCY AND MODULATION SYSTEMS

Earth Stations and Spacecraft

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This document has been approved for publication by the Management Council of the Consultative Committee for Space Data Systems (CCSDS) and represents the consensus technical agreement of the participating CCSDS Member Agencies. The procedure for review and authorization of CCSDS Recommendations is detailed in Reference [1] and the record of Agency participation in the authorization of this document can be obtained from the CCSDS Secretariat at the address below.

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STATEMENT OF INTENT

The Consultative Committee for Space Data Systems (CCSDS) is an organization officially established by the management of member space Agencies. The Committee meets periodically to address data systems problems that are common to all participants, and to formulate sound technical solutions to these problems. Inasmuch as participation in the CCSDS is completely voluntary, the results of Committee actions are termed **Recommendations** and are not considered binding on any Agency.

These **Recommendations** are issued by, and represent the consensus of, the CCSDS Plenary body. Agency endorsement of these **Recommendations** are entirely voluntary. Endorsement, however, indicates the following understandings:

- o Whenever an Agency establishes a CCSDS-related **standard**, this **standard** will be in accord with the relevant **Recommendation**. Establishing such a **standard** does not preclude other provisions which an Agency may develop.
- o Whenever an Agency establishes a CCSDS-related **standard**, the Agency will provide other CCSDS member Agencies with the following information:
 - The **standard** itself.
 - The anticipated date of initial operational capability.
 - The anticipated duration of operational service.
- o Specific service arrangements shall be made via memoranda of agreement. Neither these **Recommendations** nor any ensuing **standards** are a substitute for a memorandum of agreement.

No later than five years from its date of issuance, these **Recommendations** will be reviewed by the CCSDS to determine whether they should: (1) remain in effect without change; (2) be changed to reflect the impact of new technologies, new requirements, or new directions; or (3) be retired or canceled.

In those instances when a new version of a **Recommendation** is issued, existing CCSDS-related Agency standards and implementations are not negated or deemed to be non-CCSDS compatible. It is the responsibility of each Agency to determine when such standards or implementations are to be modified. Each Agency is, however, strongly encouraged to direct planning for its new standards and implementations towards the later version of the Recommendation.

FOREWORD

This document, which is a set of technical Recommendations prepared by the Consultative Committee for Space Data Systems (CCSDS), is intended for use by participating space Agencies in their development of Radio Frequency and Modulation systems for earth stations and spacecraft.

These Recommendations allow implementing organizations within each Agency to proceed coherently with the development of compatible Standards for the flight and ground systems that are within their cognizance. Agency Standards derived from these Recommendations may implement only a subset of the optional features allowed by the Recommendations herein, or may incorporate features not addressed by the Recommendations.

In order to establish a common framework within which the Agencies may develop standardized communications services, the CCSDS advocates adoption of a layered systems architecture. These Recommendations pertain to the physical layer of the data system. Within the physical layer, there are additional layers covering the technical characteristics, policy constraints, and procedural elements relating to communications services provided by radio frequency and modulation systems. Recommendations contained in this document have been grouped into separate sections representing technical, policy, and procedural matters.

These Recommendations for Radio Frequency and Modulation Systems, Part 1: Earth Stations and Spacecraft, were developed for conventional near-earth and deep-space missions having moderate communications requirements. Part 2 will be concerned with data relay satellites and will address the needs of users requiring services not provided by the earth stations covered in this document.

The CCSDS will continue to develop Recommendations for Part 1: Earth Stations and Spacecraft, to ensure that new technology and the present operating environment are reflected. New Recommendations for Part 1, which are developed in the future, will utilize the same format and be designed to be inserted into this book. Holders of this document should make periodic inquiry of the CCSDS Secretariat, at the address on page i, to make sure that their book is fully current.

Through the process of normal evolution, it is expected that expansion, deletion, or modification to individual Recommendations in this document may occur. This document is therefore subject to CCSDS document management and change control procedures which are defined in reference [1]. Current versions of CCSDS documents are maintained at the CCSDS Web site:

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- United States Geological Survey (USGS)/USA.

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DOCUMENT CONTROL

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CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft	May 1999	Adds new recommendations 2.2.7 and 2.4.12B; updates recommendation 2.4.12A

REFERENCES

- [1] *Procedures Manual for the Consultative Committee for Space Data Systems*. CCSDS A00.0-Y-7. Yellow Book. Issue 7. Washington, D.C.: CCSDS, November 1996.
- [2] *Radio Frequency and Modulation—Part 1: Earth Stations*. Report Concerning Space Data System Standards, CCSDS 411.0-G-3. Green Book. Issue 3. Washington, D.C.: CCSDS, May 1997.
- [3] *Radio Regulations*, International Telecommunication Union, Geneva, Switzerland, 1992.
- [4] *Recommendations and Reports of the CCIR*, 1986 Plenary Assembly, Dubrovnik, Yugoslavia, 1986.
- [5] *Radio Frequency and Modulation Systems—Spacecraft-Earth Station Compatibility Test Procedures*. Report Concerning Space Data Systems Standards, CCSDS 412.0-G-1. Green Book. Issue 1. Washington, D.C.: CCSDS, May 1992.

The latest issues of CCSDS documents may be obtained from the CCSDS Secretariat at the address indicated on page i.

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CCSDS RECOMMENDATIONS FOR RADIO FREQUENCY AND MODULATION SYSTEMS

Earth Stations and Spacecraft

TELECOMMAND RECOMMENDATION SUMMARY

[illegible]

CCSDS RECOMMENDATIONS FOR RADIO FREQUENCY AND MODULATION SYSTEMS

Earth Stations and Spacecraft

SPACE-TO-EARTH RF RECOMMENDATION SUMMARY

[illegible]

2.2.7 MEDIUM-RATE TELECOMMAND SYSTEMS

The CCSDS,

considering

- (a) that most space agencies presently utilize either 8 kHz or 16 kHz subcarriers for telecommand transmissions where data rates are less than or equal to 4kbps;
- (b) that missions in the near future may require higher rates telecommanding capabilities, in the range 8 kbps to 256 kbps;
- (c) that the possibility of simultaneous ranging, telecommand transmission and telemetry reception can result in optimal utilization of the Earth station coverage time;
- (d) that ranging requires that a distinct carrier component be present in the up- and down-link signals;
- (e) that subcarrier modulation techniques require substantially more spectrum compared to other modulation techniques;
- (f) that the use of PCM/PM/Bi-phase modulation is justified when a distinct carrier component is required and only for bit rates below 2 Mbps;

recommends

- (1) that CCSDS agencies use PCM/PM/Bi-phase modulation direct on the carrier for medium rate telecommand data transmission;
- (2) that CCSDS agencies provide medium telecommand bit rates in the range $R = 4000 \cdot 2^n$ where $n=1 \dots, 6$.

2.4.8 MAXIMUM PERMISSIBLE SYMBOL ASYMMETRY FOR DIGITAL SIGNALS AT THE INPUT TO THE RF MODULATOR

The CCSDS,

considering

- (a) that symbol asymmetry^{1,2} (also referred to as mark-to-space ratio) results in unwanted spectral components in the spacecraft's transmitted RF signal;
- (b) that such unwanted spectral components can cause harmful interference to other users of the frequency band;
- (c) that for a wide range of symbol³ rates, current technology permits control of the symbol asymmetry such that these components can be reduced to a level of -60 dBc or lower;
- (d) that, in addition to unwanted spectral components, symbol asymmetry results in data power and matched filter losses which should be minimized;
- (e) that rise and fall time of digital circuits sets a limit on achievable symbol asymmetry;

recommends

that the symbol asymmetry^{1,2} shall not exceed 0.2 %.

NOTES:

- 1. Definition of: $\text{Symbol Asymmetry} = \frac{|\text{long symbol} - \text{short symbol}|}{\text{long symbol} + \text{short symbol}}$;
- 2. Symbol asymmetry shall be measured at 50% of the peak-to-peak amplitude point.
- 3. A symbol is not unambiguously defined in the literature. For purposes of this Recommendation, a symbol shall be equivalent to:
 - a bit or an encoded bit or a chip in the case of NRZ waveforms;
 - half a bit or half an encoded bit or half an encoded chip in the case of Bi-φ waveforms;
 - half of the clock cycle for a squarewave subcarrier.

**2.4.12A MAXIMUM PERMISSIBLE PHASE AND AMPLITUDE IMBALANCES FOR
SUPPRESSED CARRIER (BPSK/QPSK) RF MODULATORS FOR SPACE-TO-
EARTH LINKS, CATEGORY A**

The CCSDS,

considering

- (a) that suppressed carrier modulation (PSK) is recommended by CCSDS [401 (2.3.2) B-1] for spacecraft telemetry transmissions in the 2 and 8 GHz bands when residual carrier modulation would exceed PFD limits on the Earth's surface;
- (b) that the presence of unwanted discrete spectral lines in the received spectrum may degrade the receiver's performance;
- (c) that phase and amplitude imbalances in the modulated RF carrier, caused by imperfections in the PSK modulator, contribute to the generation of a spurious spectral line at the carrier's frequency which can be detrimental to the performance of a PSK system and which may exceed PFD constraints;
- (d) that a phase imbalance of less than 2 degrees and an amplitude imbalance of less than 0.2 dB will result in a carrier suppression of between 25 and 42 dB;
- (e) that for near-Earth missions where one can have excessive data margin, the degradation due to the cross-talk caused by the phase and amplitude imbalances in a balanced QPSK system can be tolerated up to 0.4 dB;
- (f) that although the phase and amplitude imbalances in a balanced QPSK modulator contribute to the generation of cross-talk between channels which can be detrimental to the system performance, the actual limiting factor is the PFD constraints for near-Earth missions where excessive data margin can be available;

recommends

that the modulator's phase imbalance shall not exceed 2 degrees and the amplitude imbalance shall not exceed 0.2 dB in a suppressed carrier RF modulation system, provided however that the carrier suppression shall always be 30 dB or more.

**2.4.12B MAXIMUM PERMISSIBLE PHASE AND AMPLITUDE IMBALANCES FOR
SUPPRESSED CARRIER (BPSK/QPSK) RF MODULATORS FOR SPACE-TO-
EARTH LINKS, CATEGORY B**

The CCSDS,

considering

- (a) that suppressed carrier modulation (PSK) is recommended by CCSDS [401 (2.3.2) B-1] for spacecraft telemetry transmissions in the 2 and 8 GHz Category B bands;
- (b) that the presence of unwanted discrete spectral lines in the received spectrum may degrade the receiver's performance;
- (c) that phase and amplitude imbalances in the modulated RF carrier, caused by imperfections in the PSK modulator, contribute to the generation of a spurious spectral line at the carrier's frequency which can be detrimental to the performance of a PSK system;
- (d) that, for a balanced QPSK system of which the data rate and the power are the same for both In-phase (I) and Quadrature (Q) channels, the phase imbalance between channels caused by a deviation from the ideal 90-degree separation occurs when the phase shifter at the transmitter and/or the receiver is no longer operated in the linear region;
- (e) that, for a balanced QPSK system, the phase and amplitude imbalances in the modulated RF carrier as well as the phase imbalance between channels contribute to the generation of cross-talk between channels through either a failure of maintaining the inter-channel orthogonality or an imperfect carrier tracking, which can be detrimental to the system performance;
- (f) that a phase imbalance of less than 2 degrees and an amplitude imbalance of less than 0.2 dB will result in a carrier suppression of between 25 and 42 dB;
- (g) that, for deep space missions with small data margins, the degradation due to the cross-talk caused by the phase and amplitude imbalances can be tolerated up to 0.35 dB;

recommends

- (1) that the modulator's phase imbalance shall not exceed 2 degrees and the amplitude imbalance shall not exceed 0.2 dB in order for a BPSK system to have a degradation of 0.25 dB or less at bit error rate of 10^{-3} ;
- (2) that the modulator's phase imbalance with unbalanced modulators as well as the interchannel phase imbalance shall not exceed 2 degrees and the amplitude imbalance shall not exceed 0.2 dB in order for a balanced QPSK system to have a degradation of 0.35 dB or less at bit error rate of 10^{-3} .

2.4.14A ALLOWABLE VALUES FOR TELEMETRY SUBCARRIER FREQUENCY-TO-SYMBOL RATE RATIOS FOR PCM/PSK/PM MODULATION IN THE 2 AND 8 GHz BANDS, CATEGORY A

The CCSDS,

considering

- (a) that, for Category A missions, a PCM/PSK/PM modulation scheme with a sinewave subcarrier is typically used for transmission of low data rates;
- (b) that integer subcarrier frequency-to-symbol rate ratios (n) result in a data spectral density minimum around the carrier frequency;
- (c) that the subcarrier frequency-to-symbol rate ratio (n) should be minimized to avoid unnecessary occupation of the frequency spectrum in accordance with Recommendation 401 (3.3.4) B-1;
- (d) that the lowest practicable value of n can be determined by the amount of acceptable interference from the data spectrum (I) into the carrier tracking loop bandwidth (B_L);
- (e) that, for Category A missions, a 0.3 dB degradation in the symbol detection process shall not be exceeded, which requires a 15 dB Carrier-to-Noise ratio (C/N) in the carrier tracking loop, when using CCSDS concatenated coding schemes;
- (f) that any additional degradation, due to data interference in the carrier tracking loop, shall be insignificant for which a C/I ratio greater than 20 dB is considered adequate;
- (g) that, for small ratios of symbol rate-to-carrier tracking loop bandwidth, the modulation index has to be adjusted accordingly in order to achieve the required loop SNR resulting in a nearly constant C/I versus B_L/R_S ;
- (h) that, in the presence of only one telemetry signal, a small value of n ($n = 4$) is generally sufficient to obtain the required performance under typical operating conditions for subcarrier frequencies above 60 kHz;
- (i) that for higher symbol rates, the presence of telecommand feed-through and/or ranging signals may require the selection of a slightly higher value of n ;
- (j) that CCSDS Recommendation 2.4.3 provides guidance regarding the use of subcarriers in low bit rate residual carrier telemetry systems;

recommends

- (1) that the subcarrier frequency-to-symbol rate ratio, n , be an integer value;
- (2) that a subcarrier frequency-to-symbol rate ratio of 4 be selected for subcarrier frequencies above 60 kHz unless recommends 3 applies;
- (3) that, in the case of spectral overlaps with other signal components, the minimum integer value of n be selected to permit no more than a 0.3 dB degradation in the symbol detection process.

2.4.14B ALLOWABLE VALUES FOR TELEMETRY SUBCARRIER FREQUENCY-TO-SYMBOL RATE RATIOS FOR PCM/PSK/PM MODULATION IN THE 2 AND 8 GHz BANDS, CATEGORY B

The CCSDS,

considering

- (a) that, for Category B missions, a PCM/PSK/PM modulation scheme with a squarewave subcarrier is typically used for transmission of low data rates;
- (b) that integer subcarrier frequency-to-symbol rate ratios (n) result in a data spectral density minimum around the carrier frequency;
- (c) that the subcarrier frequency-to-symbol rate ratio (n) should be minimized to avoid unnecessary occupation of the frequency spectrum in accordance with Recommendation 401 (3.3.4) B-1;
- (d) that the lowest practicable value of n can be determined by the amount of acceptable interference from the data spectrum (I) into the carrier tracking loop bandwidth (B_L);
- (e) that, for Category B missions, a 0.1 dB degradation in the symbol detection process shall not be exceeded, which requires an 18 dB Carrier-to-Noise ratio (C/N) in the carrier tracking loop, when using CCSDS concatenated coding schemes;
- (f) that any additional degradation, due to data interference in the carrier tracking loop, shall be insignificant for which a C/I ratio greater than 25 dB is considered adequate;
- (g) that, for small ratios of symbol rate-to-carrier tracking loop bandwidth, the modulation index has to be adjusted accordingly in order to achieve the required loop SNR resulting in a nearly constant C/I versus B_L/R_S ;
- (h) that, in the presence of only one telemetry signal, a small value of n ($n = 5$) is generally sufficient to obtain the required performance under typical operating conditions for subcarrier frequencies above 60 kHz;
- (i) that for higher symbol rates, the presence of telecommand feed-through and/or ranging signals may require the selection of a slightly higher value of n ;
- (j) that CCSDS Recommendation 2.4.3 provides guidance regarding the use of subcarriers in low bit rate residual carrier telemetry systems;

recommends

- (1) that the subcarrier frequency-to-symbol rate ratio, n , be an integer value;
- (2) that a subcarrier frequency-to-symbol rate ratio of 5 be selected for subcarrier frequencies above 60 kHz unless recommends 3 applies;
- (3) that, in the case of spectral overlaps with other signal components, the minimum integer value of n be selected to permit no more than a 0.1 dB degradation in the symbol detection process.

**2.4.15A MINIMUM SYMBOL RATE FOR PCM/PM/Bi- ϕ MODULATION ON A
RESIDUAL RF CARRIER, CATEGORY A**

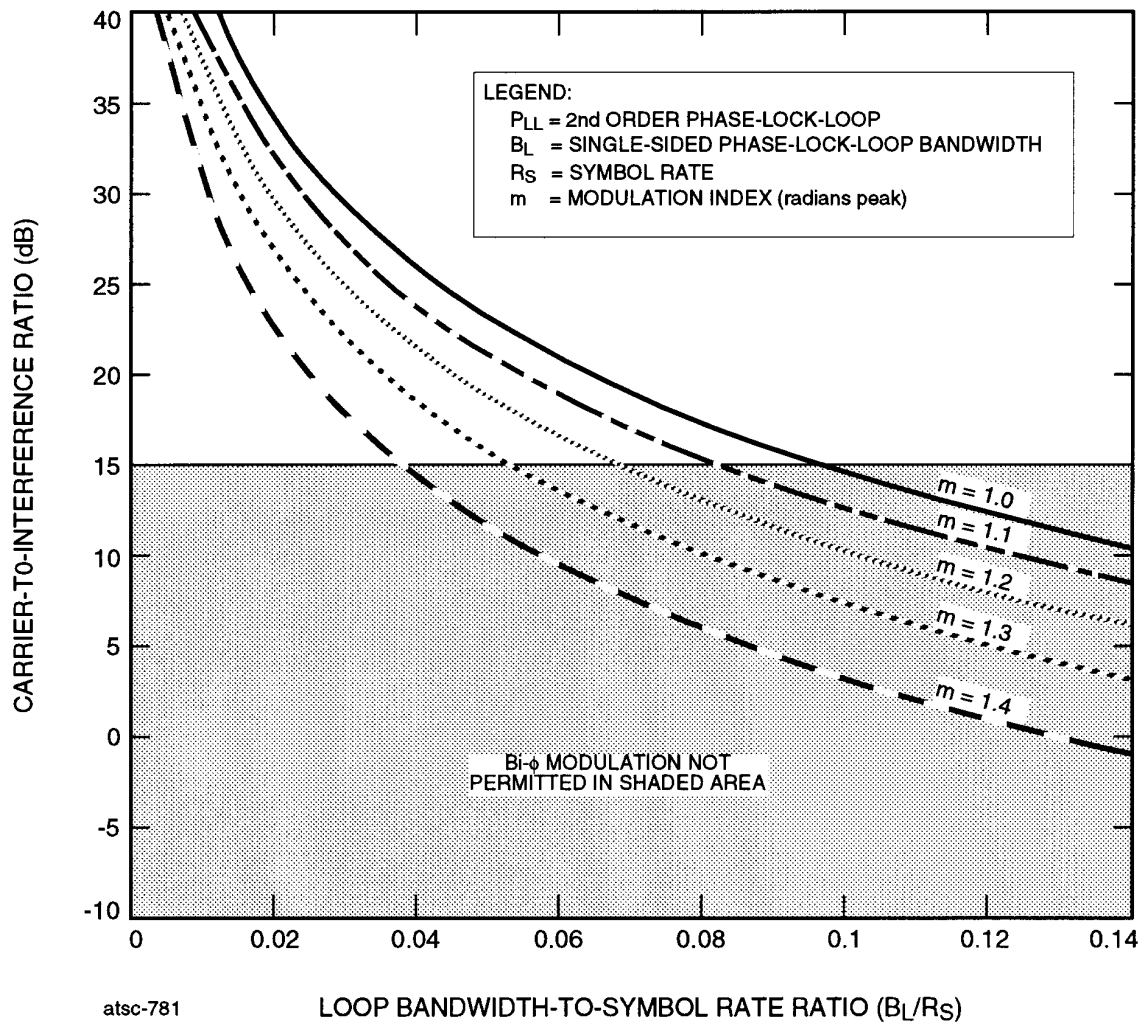
The CCSDS,

considering

- (a) that Recommendation 3.3.4 emphasizes the avoidance of a PCM/PSK/PM [subcarrier] modulation scheme whenever possible;
- (b) that data modulated on a residual carrier have spectral components which fall into the carrier tracking loop's bandwidth reducing the Carrier-to-Noise ratio (C/N);
- (c) that the level of interference is a function of the carrier tracking loop's bandwidth (B_L), the symbol rate (R_S), and the modulation index (m);
- (d) that a 0.3 dB degradation in the symbol detection process should not be exceeded requiring a Carrier-to-Noise (C/N) ratio in the carrier tracking loop of 10 dB (uncoded case) or 15 dB (CCSDS concatenated coded case);
- (e) that any additional degradation resulting from data interference in the carrier tracking loop must be insignificant requiring a Carrier-to-Interference (C/I) ratio greater than 15 dB (uncoded case) and 20 dB (CCSDS concatenated coded case);

recommends

- (1) that, when no coding is employed, Figure 2.4.15A-1 should be used for determining symbol rates (R_S), relative to loop bandwidth (B_L) where PCM/PM/Bi- ϕ modulation is not permitted;
- (2) that, when CCSDS Concatenated coding is employed, Figure 2.4.15A-2 should be used for determining symbol rates (R_S), relative to loop bandwidth (B_L), where PCM/PM/Bi- ϕ modulation is not permitted.

2.4.15A MINIMUM SYMBOL RATE FOR PCM/PM/Bi- ϕ MODULATION ON A RESIDUAL RF CARRIER, CATEGORY A (Continued)**FIGURE 2.4.15A-1: OPERATING REGION FOR USE OF PCM/PM/Bi- ϕ MODULATION WHEN NO CODING IS EMPLOYED**

2.4.15A MINIMUM SYMBOL RATE FOR PCM/PM/Bi- ϕ MODULATION ON A RESIDUAL RF CARRIER, CATEGORY A (Continued)

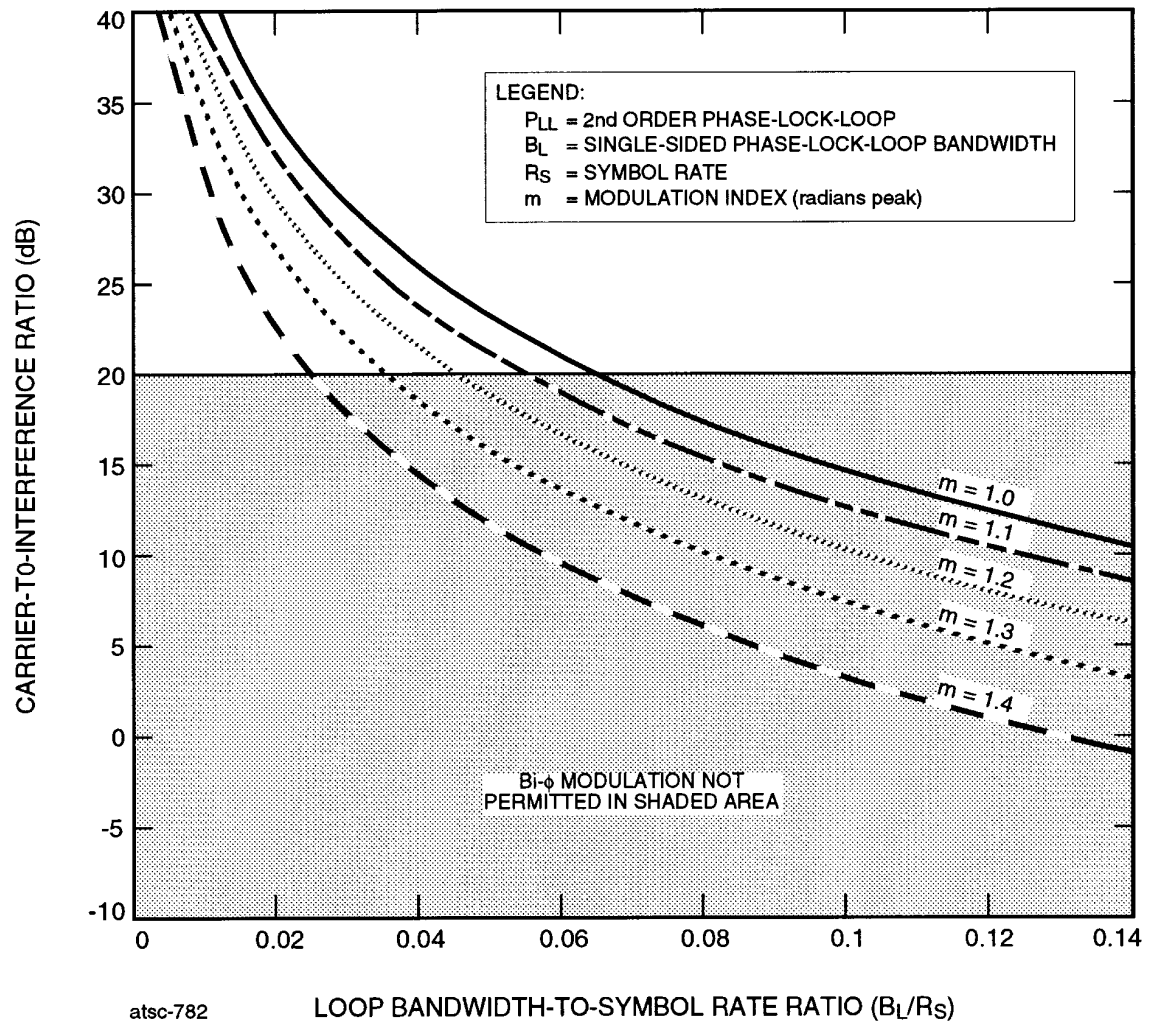


FIGURE 2.4.15A-2: OPERATING REGION FOR USE OF PCM/PM/Bi- ϕ MODULATION WHEN CCSDS CONCATENATED CODING IS EMPLOYED

**2.4.15B MINIMUM SYMBOL RATE FOR PCM/PM/Bi- ϕ MODULATION ON A
RESIDUAL RF CARRIER, CATEGORY B**

The CCSDS,

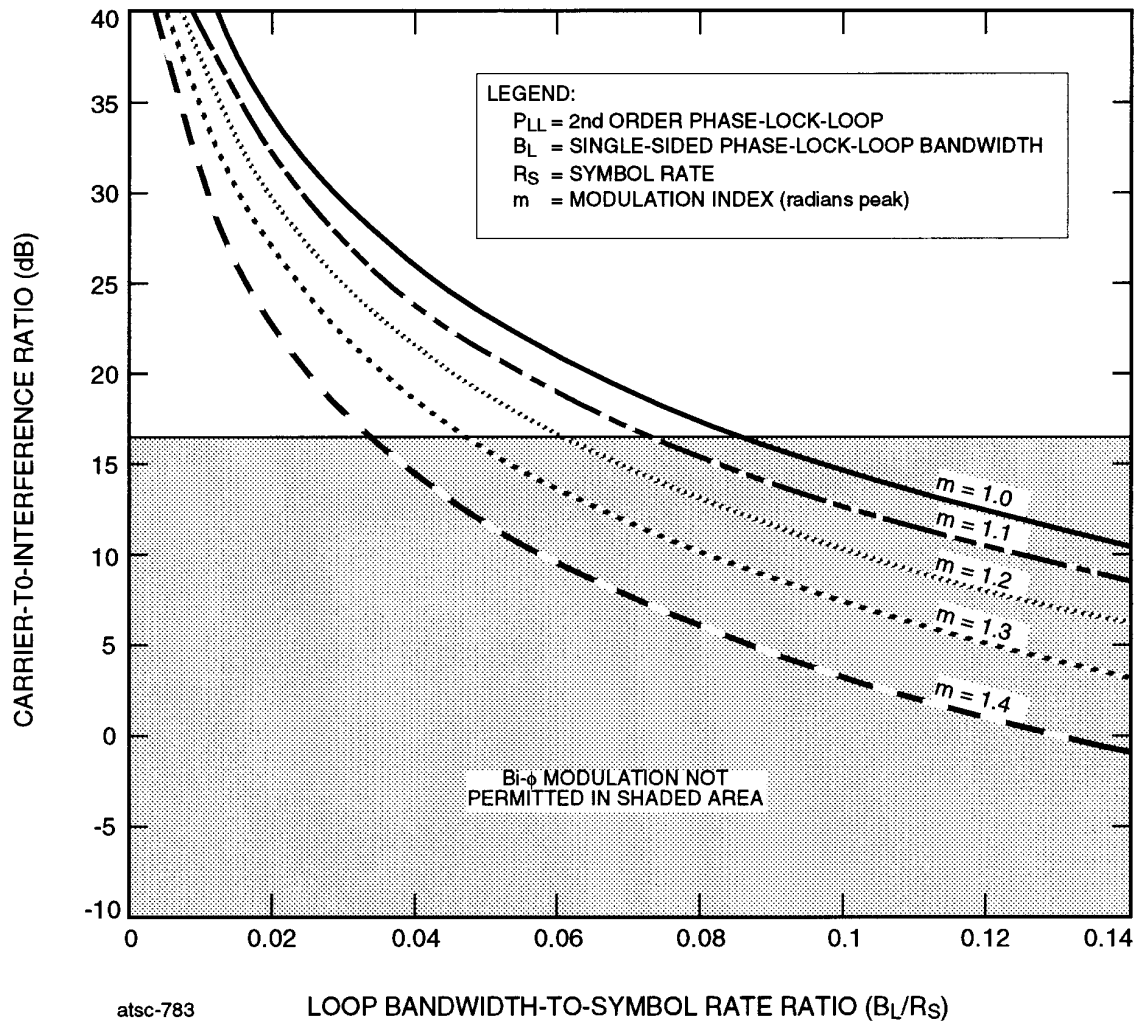
considering

- (a) that Recommendation 3.3.4 emphasizes the avoidance of a PCM/PSK/PM [subcarrier] modulation scheme whenever possible;
- (b) that data modulated on a residual carrier have spectral components which fall into the carrier tracking loop's bandwidth reducing the Carrier-to-Noise ratio (C/N);
- (c) that the level of interference is a function of the carrier tracking loop's bandwidth (B_L), the symbol rate (R_S), and the modulation index (m);
- (d) that a 0.1 dB degradation in the symbol detection process should not be exceeded requiring a Carrier-to-Noise (C/N) ratio in the carrier tracking loop of 12 dB (uncoded case) or 18 dB (CCSDS concatenated coded case);
- (e) that any additional degradation resulting from data interference in the carrier tracking loop must be insignificant requiring a Carrier-to-Interference (C/I) ratio greater than 17 dB (uncoded case) and 25 dB (CCSDS concatenated coded case);

recommends

- (1) that, when no coding is employed, Figure 2.4.15B-1 should be used for determining symbol rates (R_S), relative to loop bandwidth (B_L) where PCM/PM/Bi- ϕ modulation is not permitted;
- (2) that, when CCSDS Concatenated coding is employed, Figure 2.4.15B-2 should be used for determining symbol rates (R_S), relative to loop bandwidth (B_L), where PCM/PM/Bi- ϕ modulation is not permitted.

2.4.15B

MINIMUM SYMBOL RATE FOR PCM/PM/Bi- ϕ MODULATION ON A
RESIDUAL RF CARRIER, CATEGORY B (Continued)FIGURE 2.4.15B-1: OPERATING REGION FOR USE OF PCM/PM/Bi- ϕ MODULATION
WHEN NO CODING IS EMPLOYED

2.4.15B MINIMUM SYMBOL RATE FOR PCM/PM/Bi- ϕ MODULATION ON A RESIDUAL RF CARRIER, CATEGORY B (Continued)

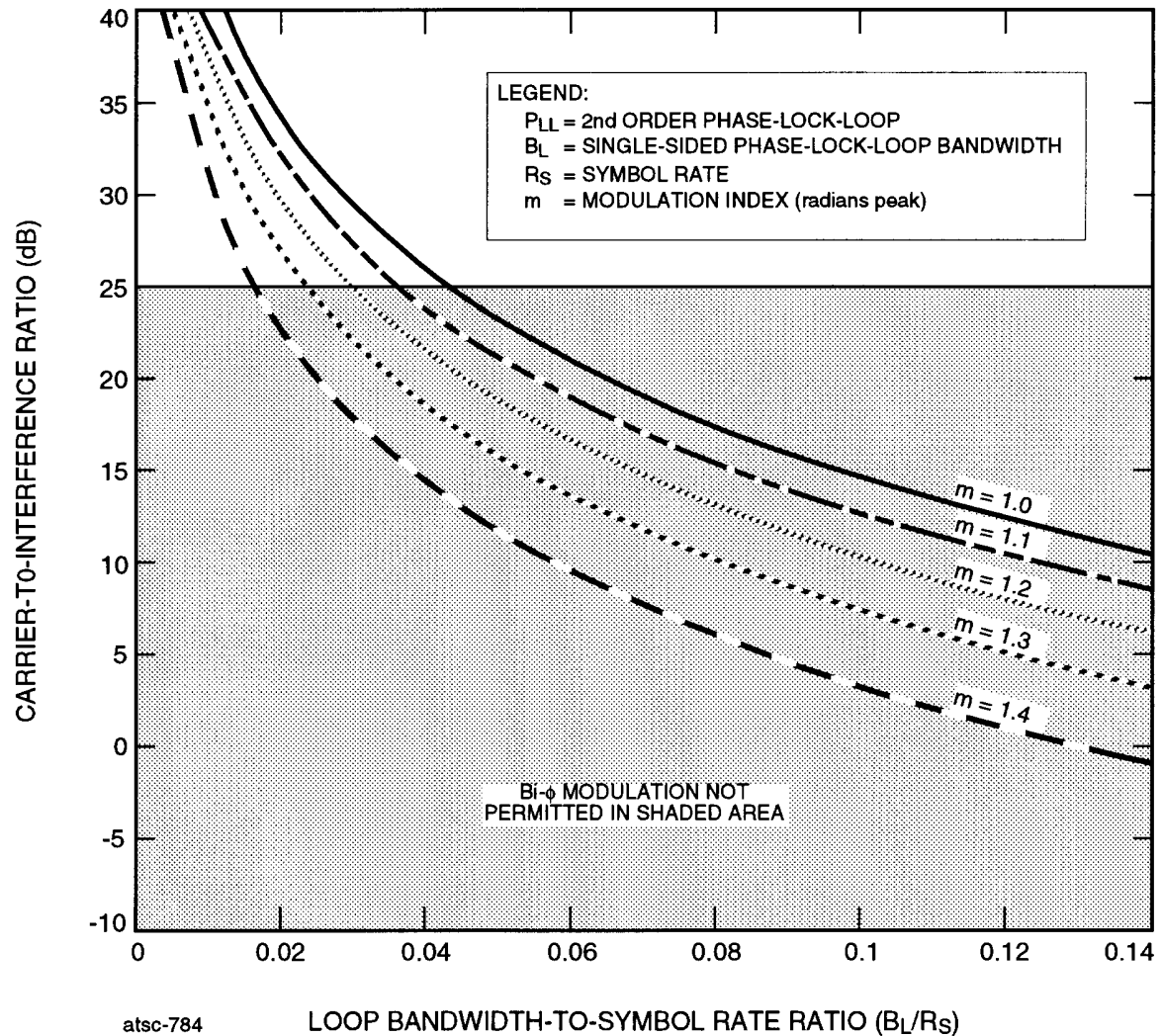


FIGURE 2.4.15B-2: OPERATING REGION FOR USE OF PCM/PM/Bi- ϕ MODULATION WHEN CCSDS CONCATENATED CODING IS EMPLOYED

2.4.16 MAXIMUM PERMISSIBLE SPURIOUS EMISSIONS

The CCSDS,

considering

- (a) that spurious emissions (ITU-RR-139) in the form of spectral lines can cause harmful interference to receiving stations operating in the allocated or adjacent frequency bands;
- (b) that such spurious emissions are caused by technological imperfections in the transmitting station, such as asymmetry of the baseband modulating waveform and crosstalk of the operating frequencies on the electronic power conditioners;
- (c) that current technology permits reduction of these spectral components to -60 dBc or lower;
- (d) that protection criteria specified for neighboring *radiocommunication services* may require additional reduction of spectral components;
- (e) that filtering can be applied if further reduction in the level of spectral components is required;

recommends

that the total power contained in any single spurious emission shall not exceed -60 dBc ¹.

NOTE:

1. dBc is measured with respect to the unmodulated carrier level's total power.

2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B

The CCSDS,

considering

- (a) that Very Long Baseline Interferometry (VLBI) measurement allow determination of geometric delay for space radio sources by the simultaneous reception and processing of radio signals at two stations;
- (b) that using the VLBI geometric delay measurements from two stations, the angular position of a spacecraft can be accurately determined for navigational purposes;
- (c) that the VLBI technique requires differencing phase measurements of sinusoidal tones or harmonics (known as Differential One-way Ranging [DOR] tones), modulated on the spacecraft's downlink RF carrier, which have been acquired at two (or more) stations;
- (d) that VLBI accuracy depends upon a priori knowledge of both the length and orientation of the baseline vector between the stations, the station clock drift, and the media delays;
- (e) that measurement errors can be greatly reduced by observing a quasar or Extra-Galactic Radio source (EGRS), that is angularly near the spacecraft, and then differencing the delay measured from the ERGS observation with the delay measured from observing the spacecraft (Δ DOR);
- (f) that the spacecraft delay measurement's precision depends upon the received power (P_{DOR}) in the two most widely spaced DOR tones, f_{BW} Hz apart, as shown in the error relationship:

$$\epsilon_{\tau} = \left[f_{BW} \sqrt{4 \pi \frac{P_{DOR}}{N_0} T_{obs}} \right]^{-1} \text{ seconds, where:}$$

$$\begin{aligned} f_{BW} &= \text{DOR tone spanned bandwidth (Hz)} \\ T_{obs} &= \text{observation time (seconds);} \end{aligned}$$

- (g) that a narrow spanned bandwidth is needed for integer cycle ambiguity resolution because the Δ DOR time delay ambiguity equals the reciprocal of the minimum spanned bandwidth;
- (h) that, contrary to considering (g), a wide spanned bandwidth is needed for high measurement accuracy;
- (i) that doubling the spanned bandwidth of spacecraft DOR tones, while holding the other parameters fixed, will reduce errors resulting from low spacecraft SNR, low quasar SNR, and instrument phase ripple by half;
- (j) that delay ambiguities in observables generated from wider bandwidths are resolved successively by using delay estimates from the narrower spanned bandwidths;

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2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Cont.)

- (k) that a typical Δ DOR error budget is dominated by errors due to low quasar SNR, quasar position uncertainty, instrument phase ripple, and the troposphere;
- (l) that EGRS delay measurement precision and instrument errors vary as $1/f_{BW}$;
- (m) that direct phase modulation of a sinewave tone on the downlink RF carrier is more spectrum efficient than squarewave modulation and allows appropriate choices of spanned bandwidth and tone power;
- (n) that the received spacecraft DOR tone power must be adequate for tone detection, with the threshold approximately determined by:

$$Threshold = \left[\frac{P_{DOR}}{N_0} \right] = 13 \text{ dB} \bullet \text{Hz if no carrier aiding is used;}$$

- (o) that the DOR tone threshold reduces to:

$$Threshold = \left[\frac{P_{DOR}}{N_0} \right] = 1 \text{ dB} \bullet \text{Hz provided that the spacecraft RF carrier's SNR is greater than 13 dB and that the extracted carrier phase is used to aid in tracking}$$

the DOR

tone whose frequency is a coherent submultiple of the spacecraft's RF carrier frequency;

- (p) that the stability of the spacecraft's RF carrier stability, over a 1-second averaging time, must be adequate for signal detection;
- (q) that the stability of the spanned bandwidth of the DOR tones, over a 1000-second averaging time, must be adequate for converting the measured phase difference to time delay;
- (r) that the *Space Research service* frequency allocation for Category B missions is 10 MHz in the 2 GHz band, 50 MHz in the 8 GHz band, 400 MHz in the 32 GHz band, and 1 GHz in the 37 GHz band;
- (s) that quasar flux is reduced and system noise temperature is higher at 32 and 37 GHz as compared to 8 GHz;

recommends

- (1) that DOR tone be sinewaves;
- (2) that either direct tone detection or carrier-aided tone detection be used;
- (3) that DOR tones be coherent with the downlink RF carrier frequency if carrier-aided detection is used;
- (4) that one DOR tone pair be used in the 2 GHz band, two DOR tone pairs be used in the 8 GHz band, and three DOR tone pairs be used in the 32 and 37 GHz bands;

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2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Cont.)

- (5) that the approximate DOR tone frequencies used in each band be those in Table 2.5.6-1;

TABLE 2.5.6-1: RECOMMENDED DOR TONES

Space-to-Earth Frequency Band	Number of DOR Tones	Approximate DOR Tone Frequencies ($\pm 10\%$)
2 GHz	1	4 MHz
8 GHz	2	4 MHz and 20 MHz
32 & 37 GHz	3	4 MHz, 20 MHz, and 120 MHz

- (6) that, if spacecraft DOR data are to be acquired in the one-way mode, the spacecraft's oscillator stability shall be:

$$\begin{aligned}\Delta f/f &\leq 4.0 \times 10^{-10} \text{ at 2 GHz,} \\ \Delta f/f &\leq 1.0 \times 10^{-10} \text{ at 8 GHz,} \\ \Delta f/f &\leq 0.3 \times 10^{-10} \text{ at 32 and 37 GHz}\end{aligned}$$

where: $\Delta f/f$ denotes the spacecraft oscillator's frequency variations;

- (7) that the frequency stability of the spanned bandwidth, f_{BW} , of the DOR tones must satisfy:

$$\Delta f_{BW}/f_{BW} \leq 1 \times 10^{-9} \text{ over a 1000-second averaging time}$$

where: Δf_{BW} denotes spanned bandwidth variations due to on-board oscillator instabilities.

3.0 POLICY RECOMMENDATIONS

Section 2 concerns itself with Recommendations pertaining to Radio Frequency and Modulation systems' technical characteristics. By contrast, this chapter focuses upon radio frequency spectrum usage.

Rules governing a user's operations in the frequency bands are as important as the equipment's technical specifications. As crowding of the RF spectrum increases, standards become an imperative to maintaining order. In a broad sense, the International Telecommunication Union (ITU) establishes high-level spectrum policy with its Radio Regulations. Here, the principal concern is to establish lower-level Recommendations promoting the most efficient use of the ITU's frequency allocations.

These policies are intended to supplement, not supplant, those promulgated by the ITU. This goal is reached by increasing the relevance of specific ITU regulations to spacecraft communications. Each Recommendation begins with applicable provisions of the ITU's Radio Regulations as a foundation and provides additional guidelines for that particular application.

By establishing the following agreements, the CCSDS agencies hope to significantly reduce spectrum congestion. Then, the potential for mutual interference in spacecraft communications should decrease accordingly.

A significant number of new Recommendations are concerned with *Policy*. Filing all such Recommendations in a single section makes them difficult to locate and promotes disorder. Accordingly, there are now six *Policy* sub-sections:

- | | | | |
|-----|------------------------------|-----|--------------------------------|
| 3.1 | <i>Frequency Utilization</i> | 3.4 | <i>Operational Procedures</i> |
| 3.2 | <i>Power Limitations</i> | 3.5 | <i>Testing Recommendations</i> |
| 3.3 | <i>Modulation Methods</i> | 3.6 | <i>Spacecraft Systems</i> |

These sub-sections are intended to be general categories into which *Policy* Recommendations can be filed and which will simplify a reader's task in locating specific items.

CCSDS RECOMMENDATIONS FOR RADIO FREQUENCY AND MODULATION SYSTEMS

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FREQUENCY UTILIZATION RECOMMENDATION SUMMARY

[illegible]

CCSDS RECOMMENDATIONS FOR RADIO FREQUENCY AND MODULATION SYSTEMS

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SPACECRAFT SYSTEMS RECOMMENDATION SUMMARY

[illegible]

**3.1.3A USE OF THE 13.25 — 15.35 GHz BANDS FOR SPACE RESEARCH,
CATEGORY A**

This recommendation has been deleted (CCSDS resolution MC-S98-3).

3.1.5B USE OF THE 31.8 — 34.7 GHz BANDS FOR SPACE RESEARCH, CATEGORY B

This recommendation has been deleted (CCSDS resolution MC-S98-3).

**3.6.1A INTERFERENCE REDUCTION IN THE 2200 - 2290 MHz BANDS,
CATEGORY A**

The CCSDS,

considering

- (a) that the planned increase in the number of links in the 2 GHz bands will raise the likelihood of harmful interference;
- (b) that channel coding techniques, such as the CCSDS concatenated codes, can reduce the power spectral density by more than 10 dB while lowering the susceptibility to interference;
- (c) that the use of suppressed carrier modulation techniques as recommended by the CCSDS, can further reduce the power spectral density;

recommends

that the power spectral density of space radiocommunication links be reduced by using appropriate modulation techniques and channel coding in accordance with CCSDS Recommendations in order to reduce the potential for harmful interference.

3.6.2A INTERFERENCE FROM SPACE-TO-SPACE LINKS BETWEEN NON-GEOSTATIONARY SATELLITES TO OTHER SPACE SYSTEMS IN THE 2025 - 2110 AND 2200 - 2290 MHz BANDS, CATEGORY A

The CCSDS,

considering

- (a) that space-to-space transmissions between two or more non-geostationary satellites shall not impose any constraints on other space transmissions (ITU-RR-750A);
- (b) that the planned increase in the number of space-to-space links between non-geostationary satellites will raise the likelihood of harmful interference;

recommends

that the power spectral density of space-to-space links between any two non-geostationary satellites be reduced by using appropriate modulation techniques and channel coding in accordance with CCSDS Recommendations, in order to reduce the potential for harmful interference to space-to-Earth, Earth-to-space, and space-to-space transmissions involving at least one geostationary satellite.

CCSDS RECOMMENDATIONS FOR RADIO FREQUENCY AND MODULATION SYSTEMS

Earth Stations and Spacecraft

COMPUTATIONAL ALGORITHMS RECOMMENDATION SUMMARY

[illegible]

4.2.2 COMPUTATIONAL METHOD FOR DETERMINING THE OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM MODULATION WITH A SINEWAVE SUBCARRIER

The CCSDS,

considering

- (a) that prior to the design of spacecraft and the assignment of frequencies, the *Occupied Bandwidth* must be known;
- (b) that the *Occupied Bandwidth* is defined as the frequency band containing 99% of the emitted power (ITU-RR-147);
- (c) that for PCM/PSK/PM modulation with an NRZ data format, a simple, exact closed form expression to calculate the *Occupied Bandwidth* is not available over the full range of applicable modulation indices;
- (d) that an approximation having better than 10% accuracy has been developed for a representative range of modulation indices;
- (e) that the *Occupied Bandwidth* can be computed with high precision using numerical integration techniques and can be plotted for easy use;

recommends

- (1) that the *Occupied Bandwidth*, B, for PCM/PSK/PM with a sinewave subcarrier be estimated by:

$$B = 4n \bullet R_s \text{ for } 0.8 < m < 1.35 \text{ and } n > 7 \text{ (in Hz)}$$

where:

n	=	subcarrier frequency-to-symbol rate ratio
R _s	=	symbol rate (s/s)
m	=	modulation index (radians peak)

- (2) that B for any other combination of m and n be determined by using Figure 4.2.2-1.

4.2.2

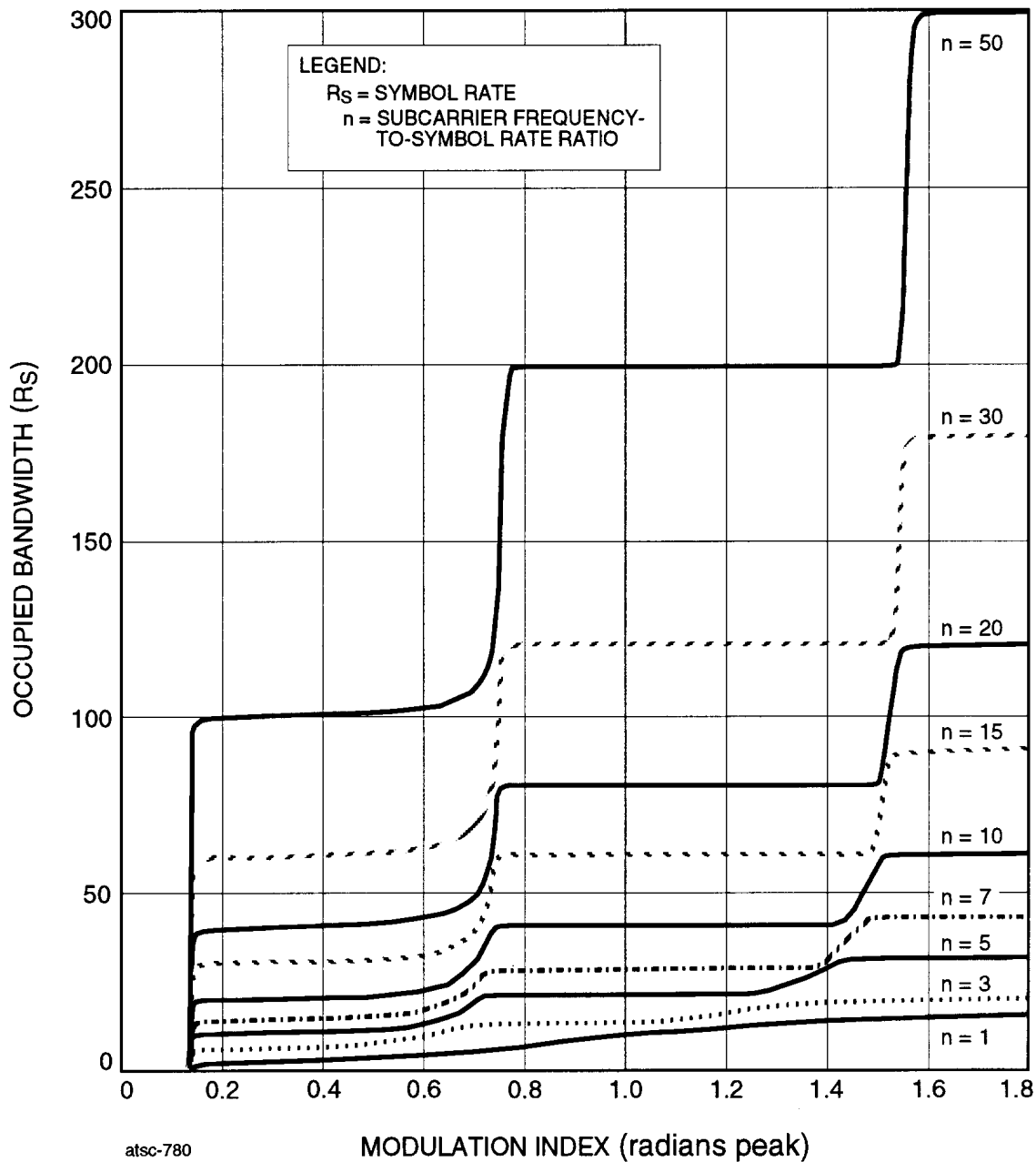
COMPUTATIONAL METHOD FOR DETERMINING THE OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM MODULATION WITH A SINEWAVE SUBCARRIER (Continued)

FIGURE 4.2.2-1: OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM SIGNAL WITH A SINEWAVE SUBCARRIER

4.2.3 COMPUTATIONAL METHOD FOR DETERMINING THE OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM MODULATION WITH A SQUAREWAVE SUBCARRIER

The CCSDS,

considering

- (a) that prior to the design of spacecraft and the assignment of frequencies, the *Occupied Bandwidth* must be known;
- (b) that the *Occupied Bandwidth* is defined as the frequency band containing 99% of the emitted power (ITU-RR-147);
- (c) that for PCM/PSK/PM modulation with an NRZ data format, a simple, exact closed form expression to calculate the *Occupied Bandwidth* is not available over the full range of applicable modulation indices;
- (d) that an approximation having better than 10% accuracy has been developed for a representative range of modulation indices;
- (e) that the *Occupied Bandwidth* can be computed with high precision using numerical integration techniques and can be plotted for easy use;

recommends

- (1) that the *Occupied Bandwidth*, B, for PCM/PSK/PM with a squarewave subcarrier be estimated by:

$$B = [(-43.2 m^3 + 103 m^2 - 2 m - 1) n + 11] \bullet R_s \text{ for } m > 0.5 \text{ radians (in Hz)}$$

where:

n	=	subcarrier frequency-to-symbol rate ratio
R _s	=	symbol rate (s/s)
m	=	modulation index (radians peak)

- (2) that B for any other combination of m and n be determined by using Figure 4.2.3-1.

4.2.3

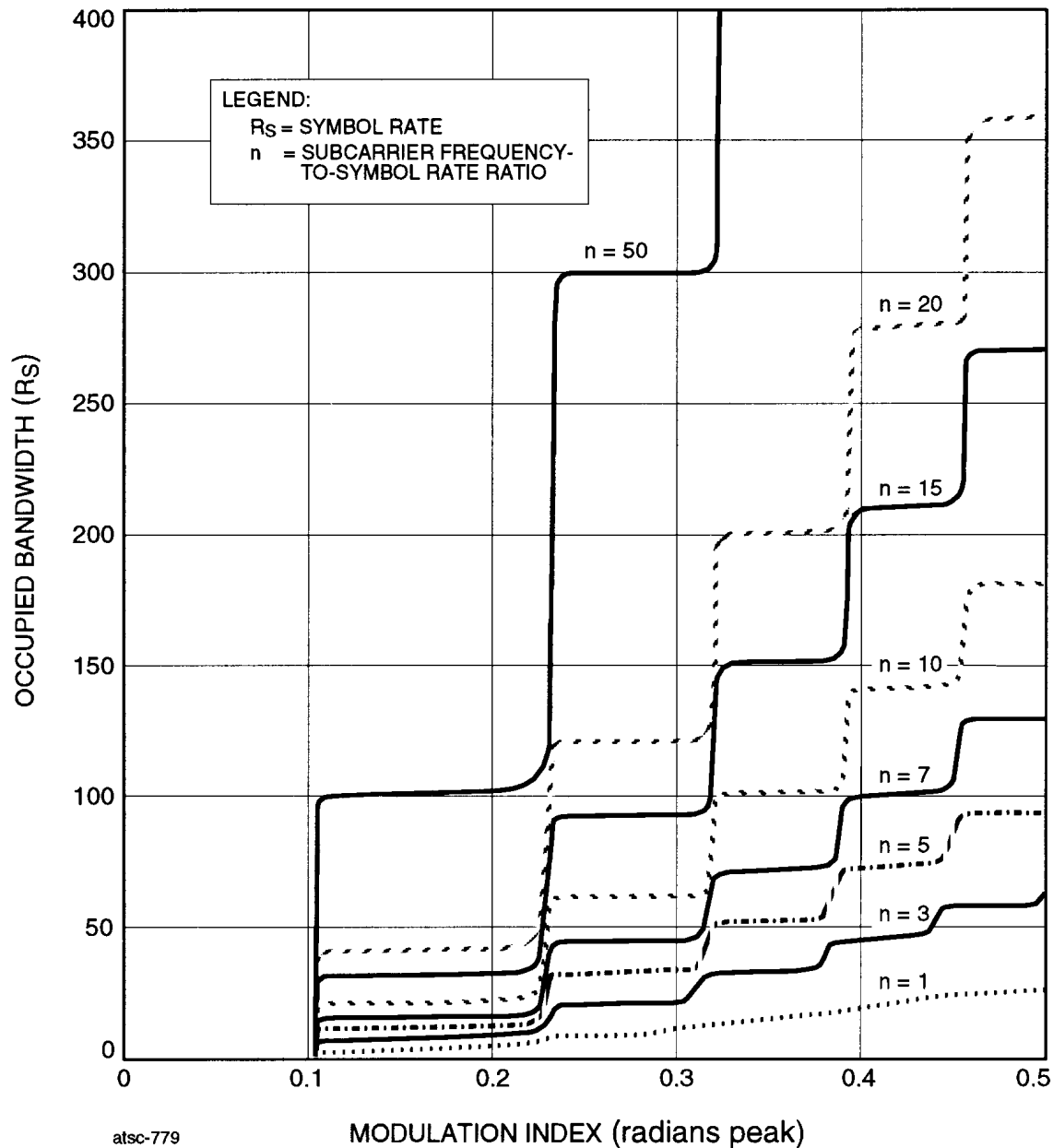
COMPUTATIONAL METHOD FOR DETERMINING THE OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM MODULATION WITH A SQUAREWAVE SUBCARRIER (Continued)

FIGURE 4.2.3-1: OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM SIGNAL WITH A SQUAREWAVE SUBCARRIER